2017 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Multi-Speed Transmission for Commercial Delivery Medium Duty Plug-In Electric Drive Vehicles

Project ID: GI161

Principal Investigator: Bulent Chavdar
Eaton Corporation
June 7, 2017

Powering Business Worldwide

Overview

Timeline

- Project Start Date: October 1, 2014
- Project End Date: October 31, 2017
- % Complete: 80%

Budget Period	Start Date	End Date
1	10/1/2014	10/31/2015
2	11/1/2015	10/31/2016
3	11/1/2016	10/31/2017

Barriers & Technical Targets:

- The public acceptance of electric vehicles will be increased with a transmission
- The performance gap between EVs and ICDVs will be reduced with a transmission
- The concept transmission will be reliable, affordable, scalable and low weight

Budget

- Project Value: $3,749,710
  - DOE Share: $2,428,655
  - FFRDC: $ 571,100
  - Eaton Share: $ 749,955 (20%)
- DOE funding to Eaton: $2,428,655
  - BP1: $ 497,660
  - BP2: $ 933,325
  - BP3: $ 997,670

Partners

- Prime: Eaton Corporation
- Subcontractors
  - Proterra, EV-OEM
  - Oak Ridge National Laboratory
  - National Renewable Energy Laboratory

Relevance/Objectives -

- Overall Objectives
  - Develop reliable, efficient, and low weight transmission for MD-EVs
  - Improve the performance and increase the public acceptance of EVs

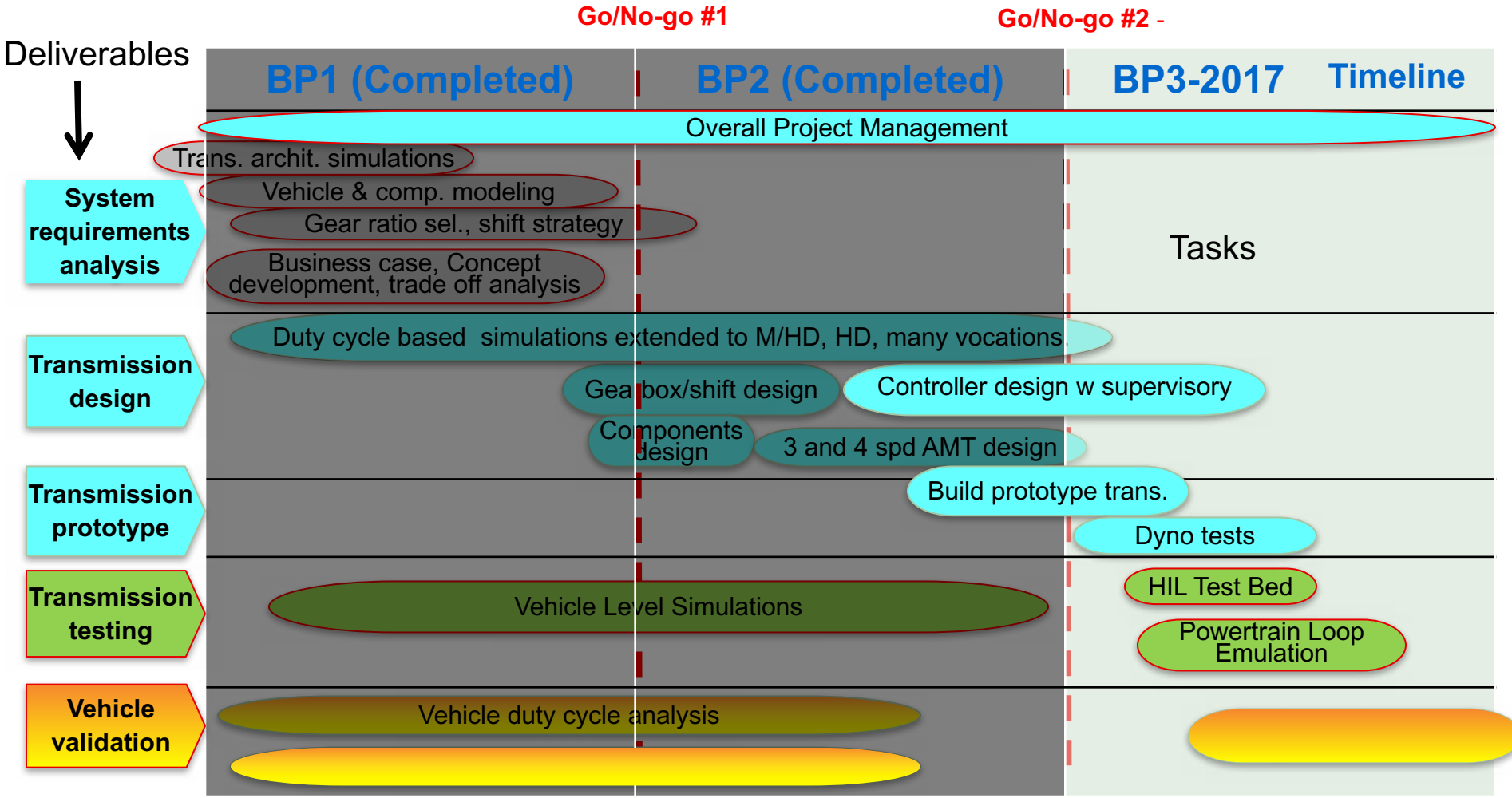
Characteristic	Units	EV with SS	EV with MS Trans.	Target Improv.
Top speed	mph	55	65+	20%
Efficiency on UDDS	mpge	29.5	32	8%
Accel. (0-50 mph)	s	90	45	50%
Gearbox efficiency	%	93.4	98	5%

- Objectives this period
  - Complete the design, the controls and the shift strategy.
  - Prototype the transmission.
  - Complete vehicle integration and validation testing. -

Approach/Strategy
EV-Transmission Project Plan

Eaton	ORNL
NREL	Proterra

Collaboration colors



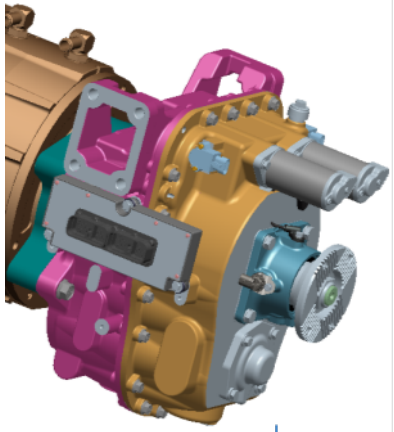
Strategy: Customer requirements analysis, system analysis, concept development, designing, prototyping, testing and validation

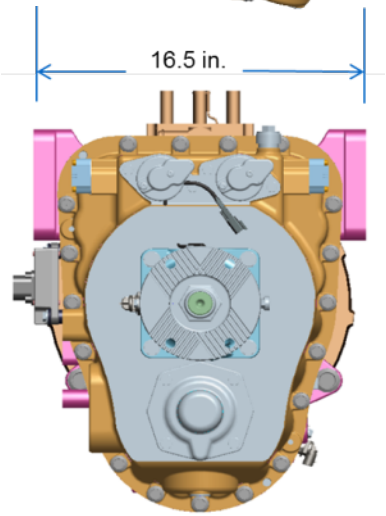
Milestones, BP3

Date	Milestone and Go/No-Go Decisions	Status
Jan. 2017	Milestone Transmission Prototyping Complete	Complete
Apr. 2017	Milestone Transmission Shakedown Testing Complete	Complete
Jul. 2017	Milestone Integrated Powertrain HIL Testing Complete	In progress
Oct. 2017	Milestone Vehicle Demonstration Complete	On track
Nov. 2017	Closeout reporting	On track

- Transmission prototyping and preliminary testing are completed.
- Integrated powertrain HIL testing is in progress.
- Vehicle integration is in progress.

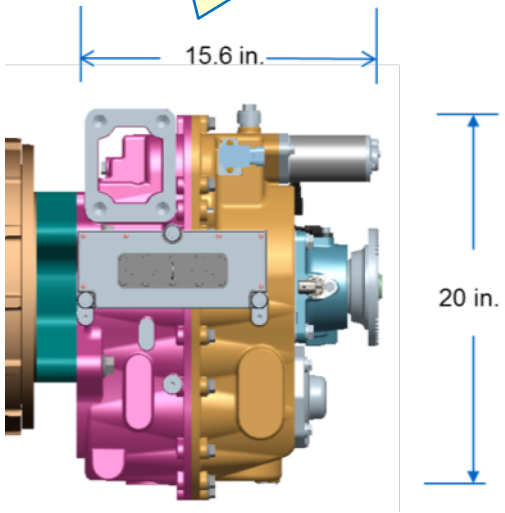
Technical Accomplishment 4-speed AMT Layout Design





- Up to 1300 N-m, 5000 rpm
- Can be configured as 3 or 4 speed
- Ratio coverage up to 9.0:1
- Flexible design accommodates multiple “gear kits” to cover a wide ratio of vehicle vocations
- Weighs 89 kg (195 lb) w/o adapter plate
- ~97% efficient

Gear	Ratio	Effic @ 100 kW, 3500 rpm	Effic @ 50 kW, 3500 rpm
1	4.82	97.5%	96.5%
2	2.61	97.5%	96.5%
3	1.65	97.5%	96.5%
4	1.00	99.0%	98.0%



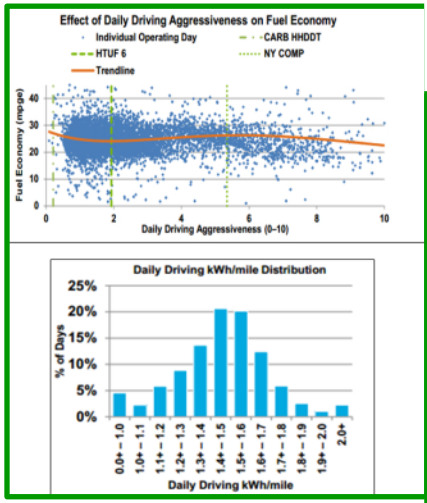
Technical Accomplishment
Modeling and simulation

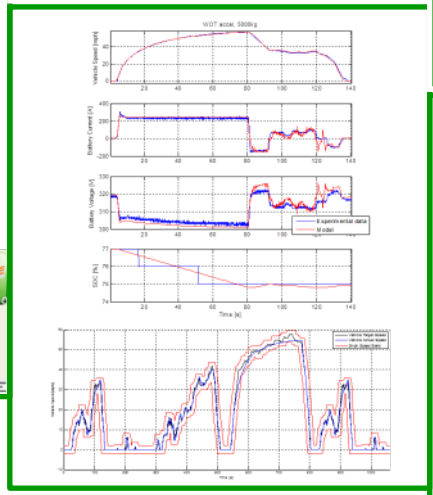
Duty cycles

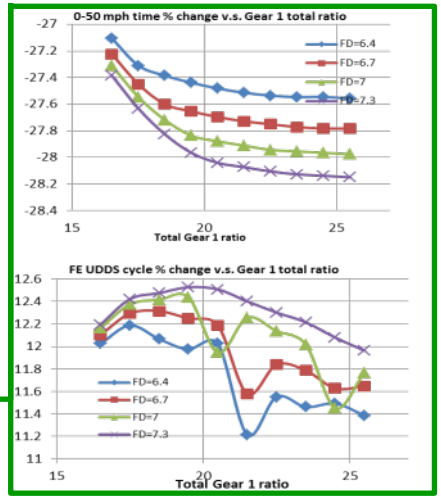
Vehicle model generation

Vehicle model validation

Gear Optimization





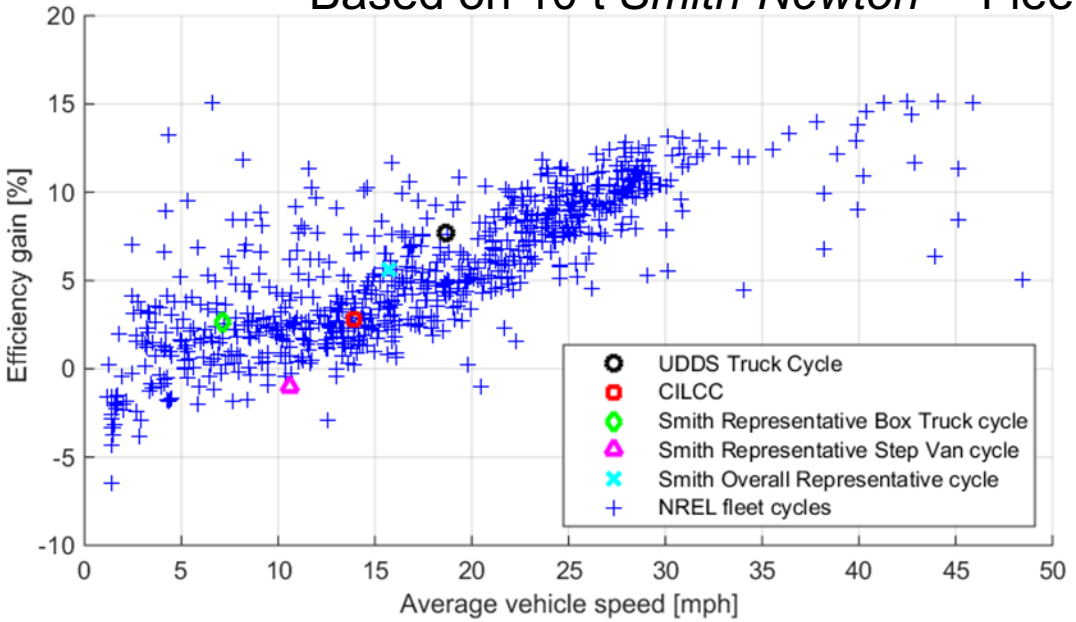


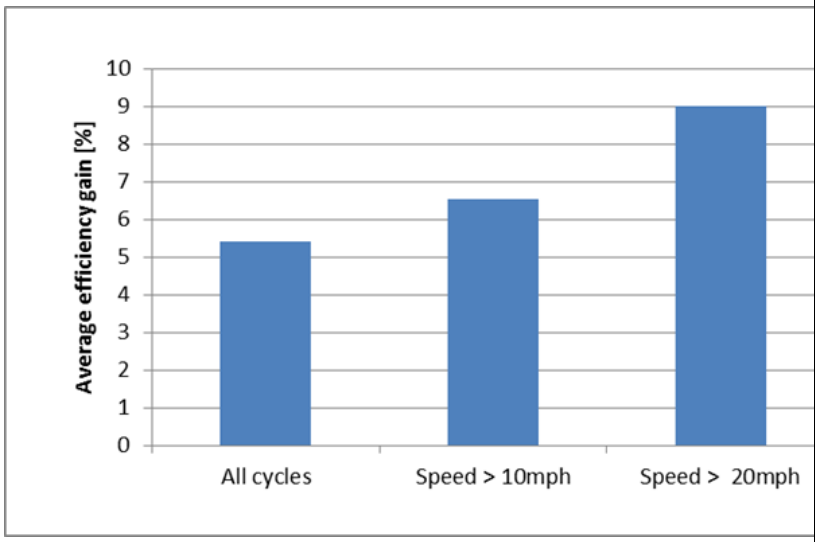
- Modeling and simulations run order

Technical Accomplishment
MD-EV Fleet Savings with 3-sp Transmission

MD-EV Fleet Analysis is done in collaboration with ORNL and NREL

Based on 10 t *Smith-Newton*™ Fleet Data provided by NREL





Efficiency gain as a function of vehicle speed for each real world cycle and standard drive cycles

- 3-speed transmission improves efficiency by 9% as compared to the single-speed gearbox at high average vehicle speeds

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Technical Accomplishment
New EV-OEM Partner Selected: Proterra

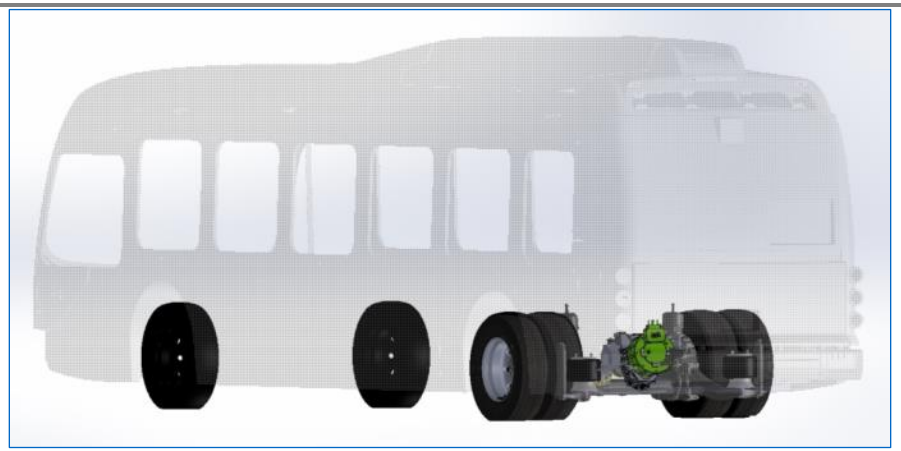
- Proterra offers 35’ and 40’ *Catalyst*™ Electric Buses

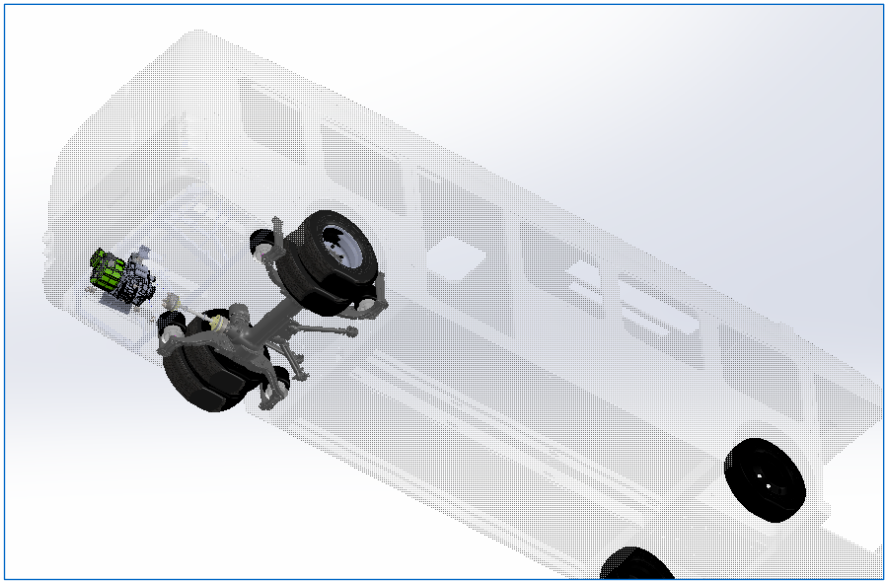
- Baseline EV uses Eaton 2-Speed

- Production facilities in
  - Greenville, SC and
  - LA County, CA

Images courtesy of Proterra

Technical Accomplishment
Trans/Powertrain Mounting in Proterra Bus





- Electric Motor
- Eaton 4-Speed Transmission
- Proterra Driveshaft and Mounting

Images courtesy of Proterra

Powertrain Analysis for BE35 Electric Bus

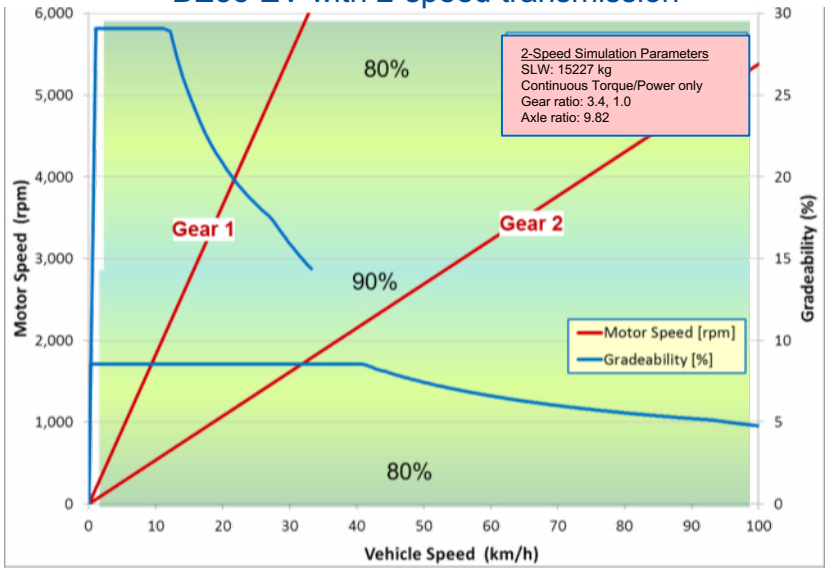
2-speed transmission vs 4-speed transmission

	Electric Bus with:	Top Speed @ GVW (mph)	Acceleration Time @ SLW (s)		Gradeability @ GVW (%)		Vehicle Efficiency @ SLW (mpg, DE)			
			0-30 mph	30-50 mph	10 mph	20 mph	UDDS	OCC	NYC	ADB
Baseline 1	2-Speed with limitations	53	15.6	27.5	15	7	20.4	19.9	17.8	20.2
Baseline 2	2-Speed w/o limitation	70	11.7	17.7	24	7.5	20.3	19.9	17.6	20.4
Simulation	4-Speed	81	9.7	16.6	24	10	23.2	23.5	20.5	24.4
Improvement over baseline 1		52.8%	37.4%	39.6%	33.3%	42.9%	13.7%	18.1%	15.8%	20.8%
Improvement over baseline 2		15.7%	17.3%	6.1%	0%	33%	14%	18%	16.4%	19.7%

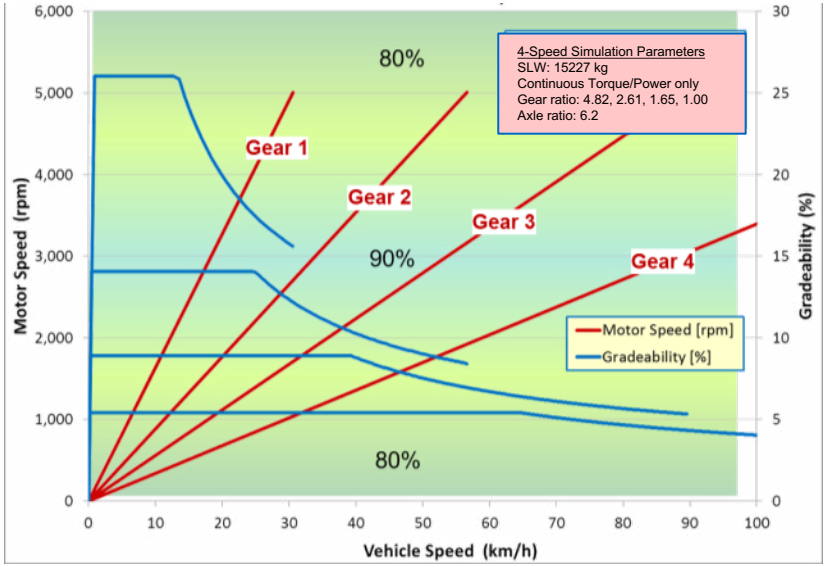
GVW: Gross Vehicle Weight: 17 t SLW: Seated Load Weight: 15 t

- 4-speed AMT improves efficiency, top speed, acceleration and gradeability.

BE35 EV with 2-speed transmission



BE35 EV with 4-speed transmission



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Technical Accomplishment
Gearset options for the 4-speed EV-AMT

Headset
Gear Ratio
Exisiting Gear
New Gear
Direct Drive

1.55	Gear Ratio	Step		1.88	Gear Ratio	Step	
4.00	2.58			4.00	2.13		
2.50	1.61	1.60	*Opt. 1*	2.50	1.33	1.60	*Option 7*
1.60	1.03	1.56		1.60	0.85	1.56	
1.00	0.65	1.60		1.00	0.53	1.60	

1.55	Gear Ratio	Step		1.88	Gear Ratio	Step	
4.26	2.75			5.17	2.75		
2.76	1.78	1.54	*Opt. 2*	3.16	1.68	1.64	*Option 8*
1.64	1.06	1.68		1.79	0.95	1.77	
1.00	0.65	1.64		1.00	0.53	1.79	

1.55	Gear Ratio	Step		1.88	Gear Ratio	Step	
4.45	2.87			5.40	2.87		
2.76	1.78	1.61	*Opt. 3*	3.16	1.68	1.71	*Option 9*
1.64	1.06	1.68		1.75	0.93	1.81	
1.00	0.65	1.64		1.00	0.53	1.75	

1.55	Gear Ratio	Step		1.88	Gear Ratio	Step	
4.82	3.11			5.85	3.11		
2.76	1.78	1.75	*Opt. 4*	3.16	1.68	1.85	*Option 10*
1.64	1.06	1.68		1.79	0.95	1.77	
1.00	0.65	1.64		1.00	0.53	1.79	

1.55	Gear Ratio	Step		1.88	Gear Ratio	Step	
6.76	4.36			8.20	4.36		
3.57	2.30	1.90	*Opt. 5*	4.08	2.17	2.01	*Option 11*
1.94	1.25	1.84		1.99	1.06	2.05	
1.00	0.65	1.94		1.00	0.53	1.99	

1.55	Gear Ratio	Step		1.88	Gear Ratio	Step	
7.29	4.70			8.84	4.70		
3.80	2.45	1.92	*Opt. 6*	4.32	2.30	2.04	*Option 12*
1.94	1.25	1.96		2.07	1.10	2.09	
1.00	0.65	1.94		1.00	0.53	2.07	

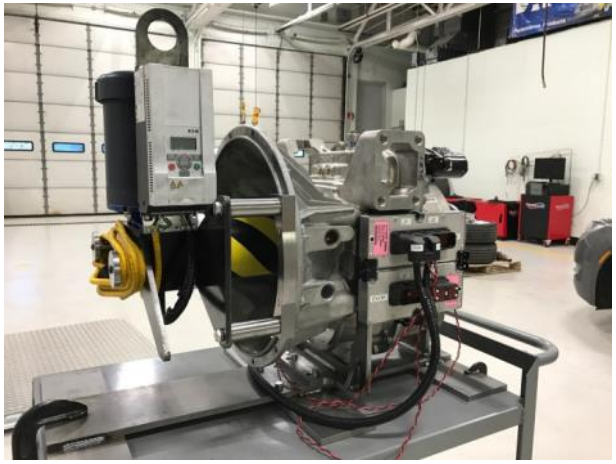
- 12 off-the-shelf gearset options are available

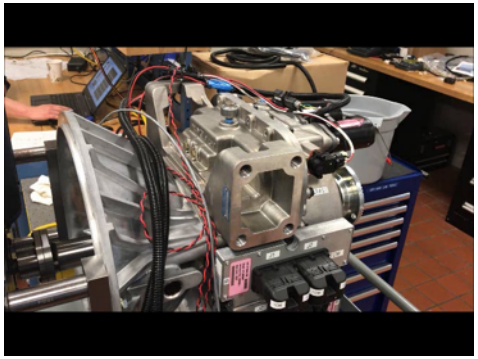
Technical Accomplishments
Novelties

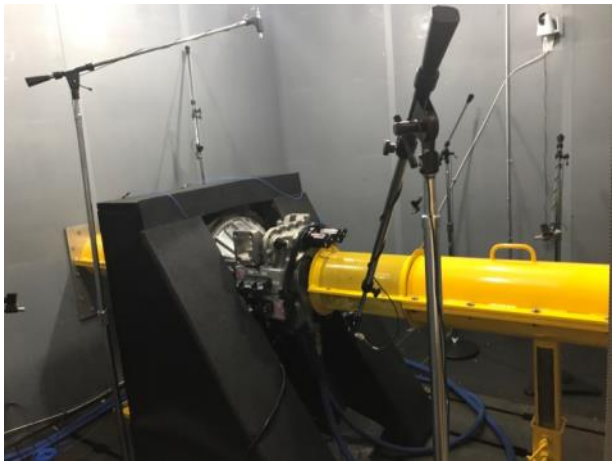
- Flexible modular design allows application commonality:
  - Choice of 12 different off-the-shelf gearset options
  - Choice of multiple final drive ratios
  - Choice of 3 or 4-speed EVs without reverse gear
  - Choice of adding a clutch, a reverse gear and a PTO for PHEVs and ICDVs
- Robust and fast shifting mechanism (Y-Y Shifters)
- Adaptive downshift strategy to maximize the regenerative braking energy
- Implementation of lightweight and additive manufacturing technologies

Technical Accomplishments
Preliminary Testing at Eaton

- Bench test setup (left)
- Initial shift calibration (center video)
- Break-in procedure on dyno (right)
- NVH testing in anechoic chamber (right)
- Efficiency testing
- Steady-state speed and torque tests







Responses to Last Year Reviewers' Comments

Reviewer: Total investment and implementation cost details need further refinement.

- Capital investment and cost details have been considered in the selection of transmission concept. The new 4-speed EV AMT meets or exceeds performance targets while requiring minimal capital investment.
- The commercialization strategy depends on the market demand. Currently, the biggest demand is in EV and PHEV segments in China.
- It is estimated that the pay back period for the 4-speed transmission is 4 to 8 years with 10% efficiency gain not counting on the impact of other performance gains. For example, savings from motor downsizing alone can offset the transmission cost.

Responses to Last Year Reviewers' Comments

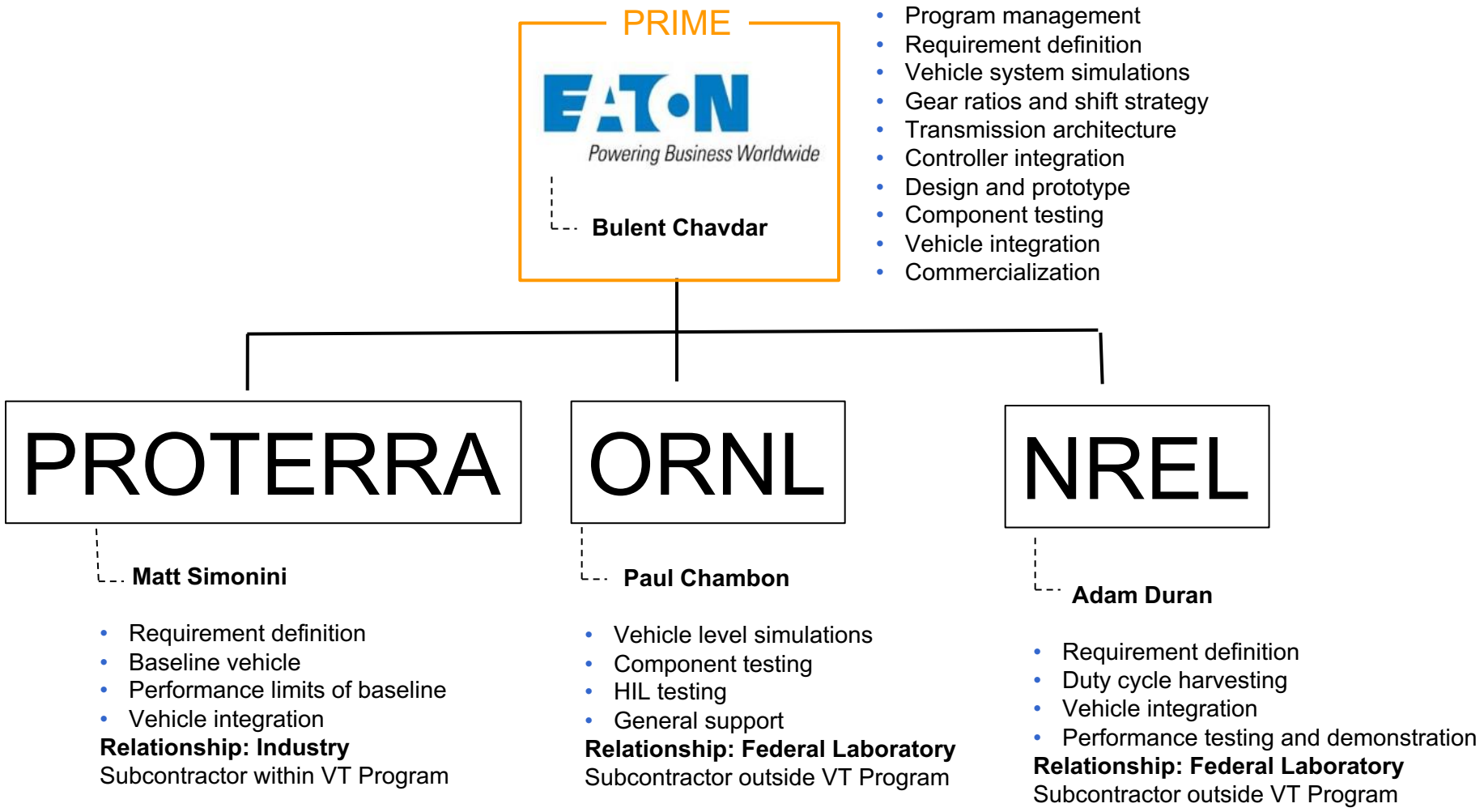
Reviewer: Lack of a vehicle partner leads to some uncertainty.

- Proterra is selected as the EV-OEM partner. Risk is mitigated.
- Protera's EV-AMT requirements were identified. Modeling and simulations were completed in BP2.
- Project is on track. All milestones have been delivered on time and on budget.

Reviewer: There will obviously be more activity by the collaborators after something is actually built.

- Vehicle integration at Proterra (in progress).
- Hardware in the Loop testing at ORNL (in progress).
- Controls, calibration and shift schedule fine tuning at Eaton (in progress).
- Validation testing of integrated vehicle at NREL.

Partners/Collaborators



Remaining Challenges and Barriers

- Completing the vehicle integration and performance verification validation tests by the end of BP3.
- Advocating the new transmission and raising the commercial interest.
- Engaging with other EV-OEMs and having them explore the benefits of multi-speed transmission.

Proposed Future Research

- Completing the transmission controls system development
- Completing the preliminary gearbox dyno testing at Eaton
  - NVH testing in anechoic chamber
  - Preliminary gearbox efficiency testing
  - Steady-state speed and torque tests
- Vehicle integration of 4-speed AMT on BE35 Electric Bus at Proterra -
- Integrated powertrain HIL testing at ORNL
  - Debugging functions, tuning controls
  - Steady-state and transient testing
  - Validate the energy efficiency achievements
- Fine tuning of shift control strategy on Eaton Proving Grounds
- Integrated Vehicle Testing at NREL

Any proposed future work is subject to change based on funding levels.

Summary of Results

- 4-speed EV-AMT has advantage over the baselines (direct drive, 1-speed, or 2-speed):
  - System energy efficiency (as high as 20%)
  - Top speed (as high as 50%)
  - Acceleration (as high as 40%)
  - Gradeability (as high as 40%)
- Zero to 50 mph acceleration time is 27 seconds for a 15 ton Electric Bus with 4-speed EV-AMT and 220/135 kW, 700 Nm motor.
- Meeting or exceeding every target set at the beginning of project.

2017 DOE Vehicle Technologies Office Annual Merit

Technical Backup Slides

"This presentation does not contain any proprietary, confidential, or otherwise restricted information."

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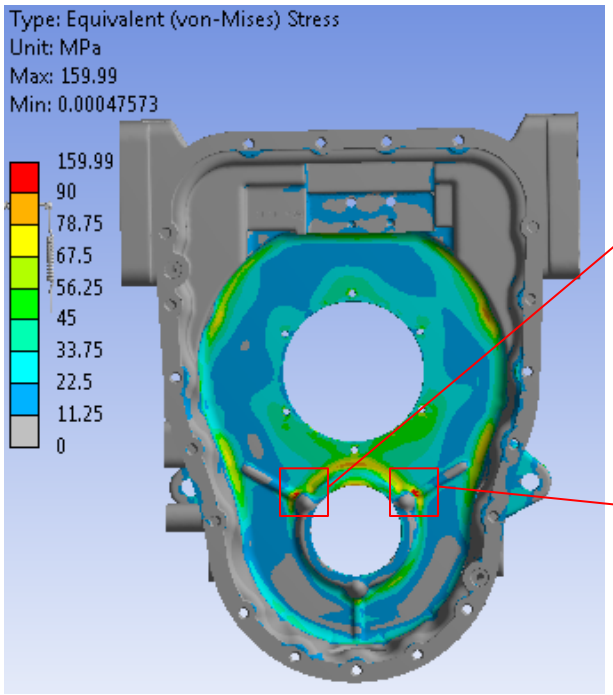
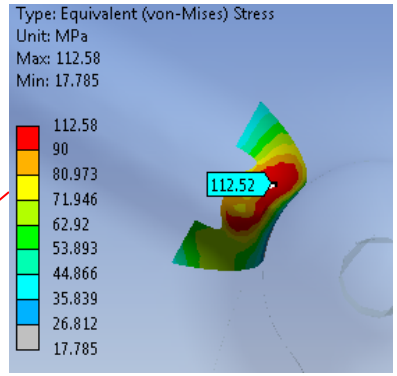
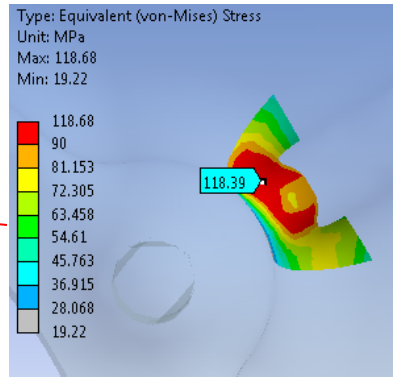
FEA of Front Housing, Fatigue Endurance

1300Nm, +4.5G, +5.5G, +2.5G,-D

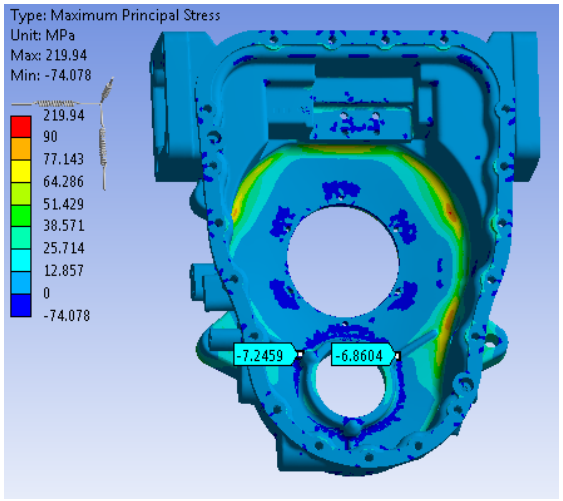
Equivalent Stress







Max Principal Stress

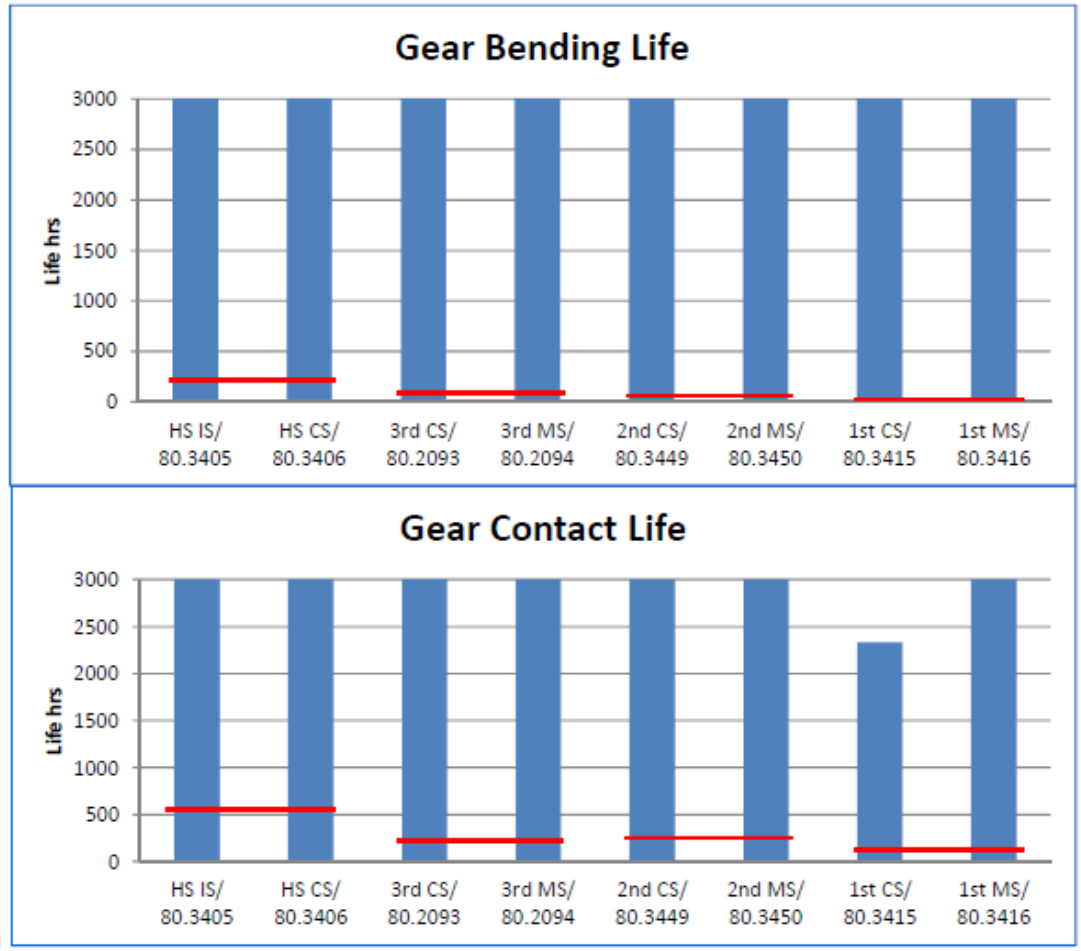


- The highlighted red regions show higher stresses > 90 MPa.

Gear life analyses: B1 Life as per ISO6336

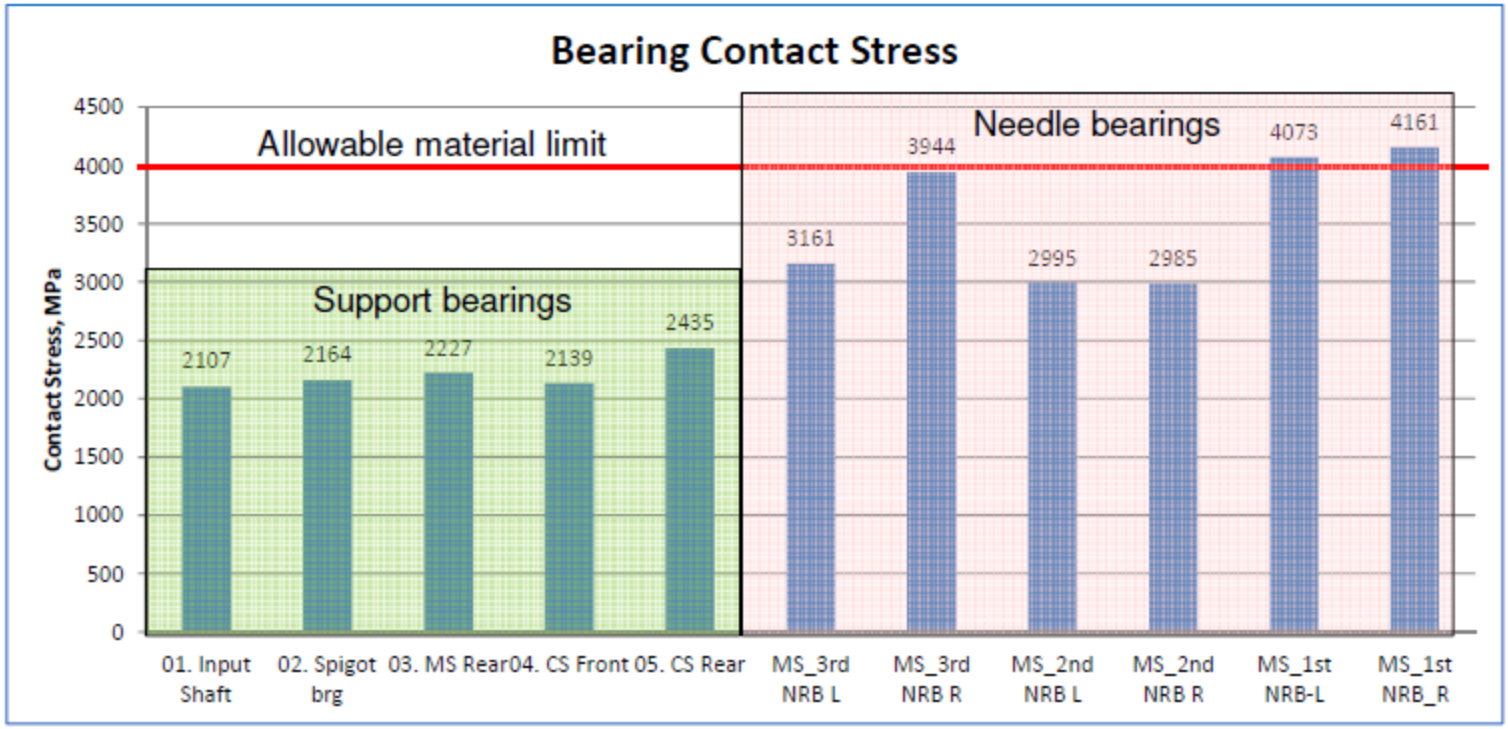
Required bending life

Required contact life



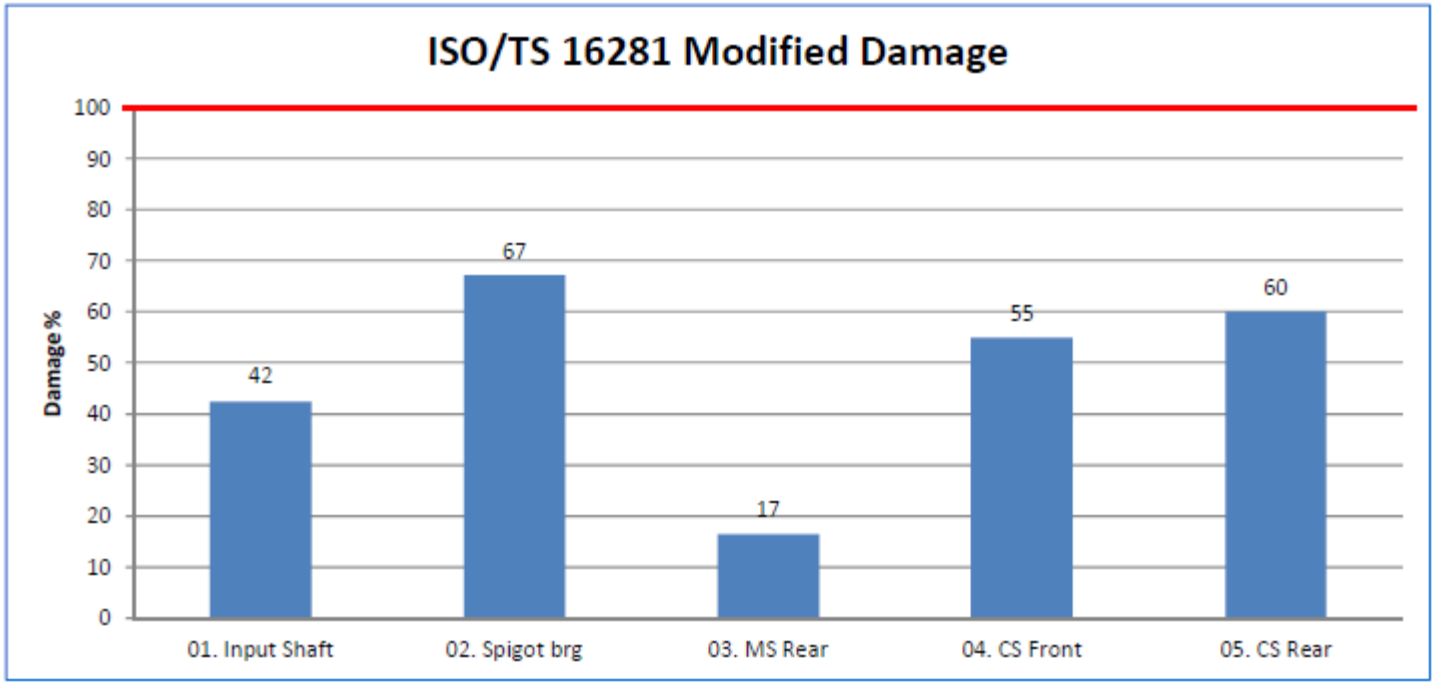
- Gear bending life and gear contact life exceed the requirements

Bearing analyses: Contact stress



- All support bearings have contact stress below material limit (4000 Mpa)
- Needle bearings have higher contact stress in braking/coast condition (-ve torque)
  - Remedy: Limit the input torque at reverse to one half of full torque

Bearing analyses: Damage as per ISO/TS16281



- All bearings have damage within acceptable limits (<100%)

NVH analysis of the 4-speed EV-AMT

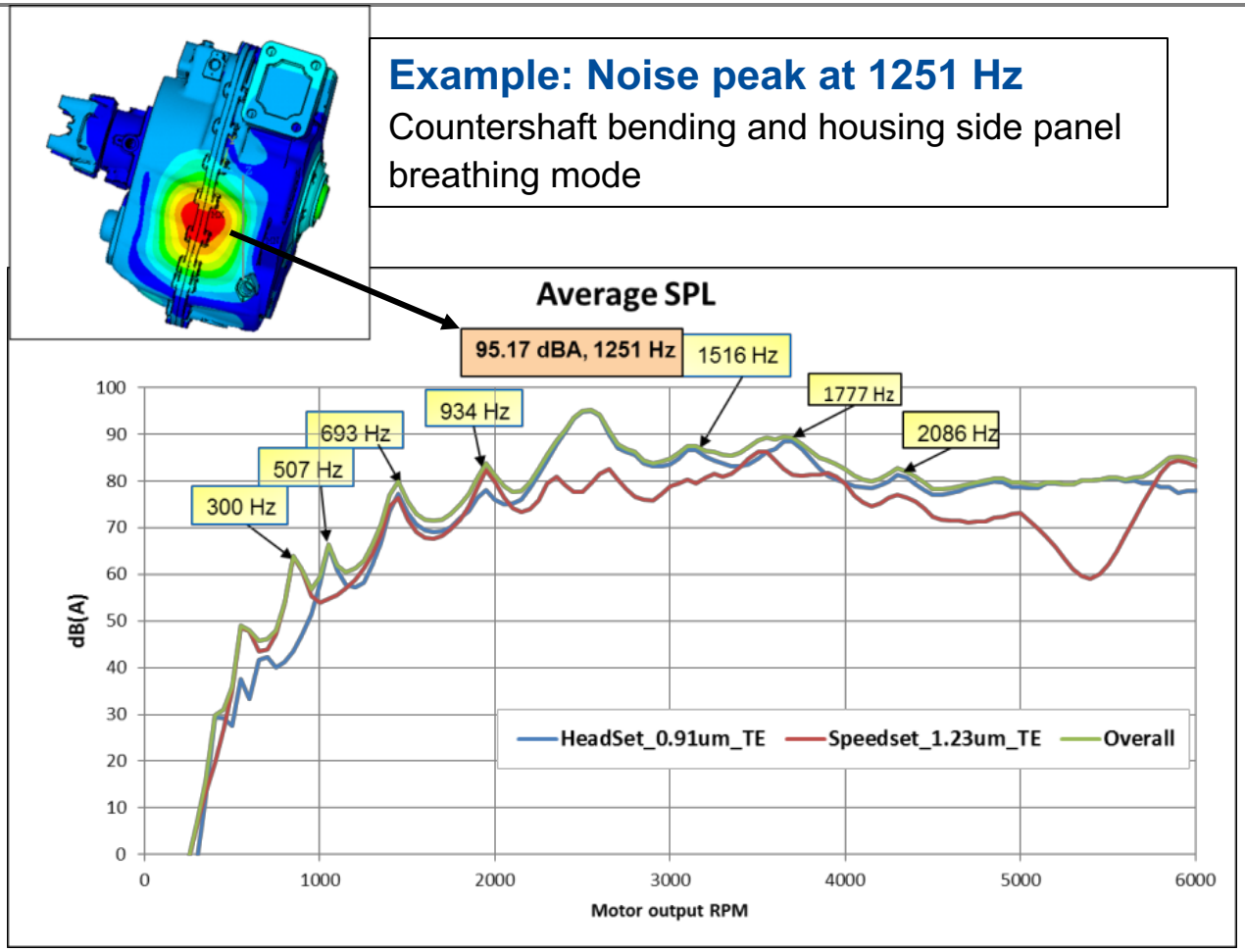
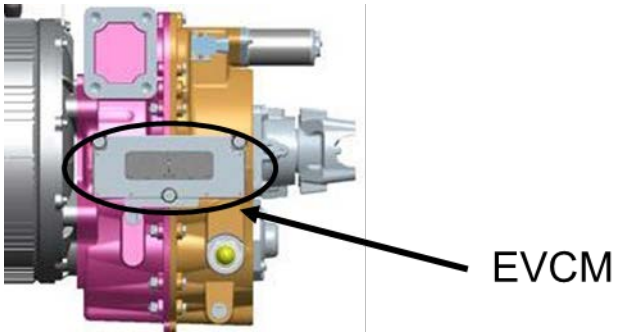


Figure 19. Average Sound Pressure Level (SPL) as function of motor output speed.

- NVH analysis will guide the product design refinement process

Controls Software Activities

- The multi-speed EV transmission is controlled by the Electric Vehicle Control Module (EVCM) and is integrated into the prototyped vehicle (Proterra).
- The EVCM is an Eaton production controller with modified controls software.



- The controls software is bench-tested at Eaton on the prototyped transmission unit prior to vehicle integration at Proterra.
  - Initial testing at Eaton – March-April, 2017
  - Target date of vehicle integration – June 2017

Publications and presentations

1. Chavdar, B., 2015-DOE-AMR PowerPoint Presentation at Arlington, Washington, on June 11, 2015. Project ID-vss161, Multi-Speed Transmission for Commercial Delivery Medium Duty Plug-In Electric Drive Vehicles.
2. Chavdar, B., FY 2015 Vehicle Systems Annual Progress Report (FY2016 VS APR), September, 2015.
3. Chavdar, B., 2016-DOE-AMR PowerPoint Presentation at Arlington, Washington, on June 9, 2016. Project ID-vss161, Multi-Speed Transmission for Commercial Delivery Medium Duty Plug-In Electric Drive Vehicles
4. Chavdar, B., Deng, Y., Naghshtabrizi, P., Genise, T., "Modular Multi-Speed Transmission for MD EV", CTI Symposium China, Automotive Transmissions, HEV and EV Drives, 5th International Congress and Expo, 21-23 September, 2016, Shanghai, China.
5. One display unit of the new 4-speed EV Transmission was displayed at the IAA Commercial Vehicles Trade Fair in Hannover on September 22-29, 2016.
6. Chavdar, B., FY 2016 Vehicle Systems Annual Progress Report (FY2016 VS APR), October, 2016.
7. Chavdar, B., Genise, T., Naghshtabrizi, P., Papp, G., "Development of Robust and Modular Drive System for MD-EV", 11th International CTI Symposium, Automotive Transmission, HEV and EV Drives, 15-18 May, 2017, Novi, MI, USA.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